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PRECERAMIC POLYMER PYROLYSIS

I. PYROLYTIC PROPERTIES OF POLYSILAZANES

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SUMMARY

The physicochemical behavior of characterized polysilazanes has been examined during their pyrolytic transformation into amorphous, silicon based, ceramics. Selected polysilazanes bearing different substituents at silicon and nitrogen were synthesized by ruthenium catalyzed dehydrocoupling of Si-H bonds with N-H bonds. The relationships between the stucture and chemical content of polymers and their pyrolyzed ceramic compositions and yields are discussed. The thermal reactivity during the pyrolysis is established by a set of hypotetical mechanisms that may occur during the heating process. The decomposition product patterns at different temperature levels and the compositions of the final ceramics suggest specific kinetically or thermodynamically controlled thermolysis pathways. Additional chemical reactivity has been observed when the amorphous ceramic products at 800°C are heated and crystallized at 1600°C.

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INORGANIC POLYMER PYROLYSIS

I. SILAZANE PRECERAMICS AND THEIR PYROLYTIC PROPERTIES

Yigal D. Blum*, Kenneth B. Schwartz and Richard M. Laine

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1. Introduction

The thermolytic conversion of chemicals to ceramics is one of the steadily growing fields in advanced material science [1]. New ceramic applications such as CVD coatings, sol-gel derived high performance glasses, and polymer-derived ceramic fibers are a result of the chemical reactivity and processability of organometallic or inorganic compounds and polymers. In particular, polysilane and polycarbosilane precursors to silicon carbide (SiC) and polysilazane precursors to silicon nitride (Si_3N_4) are important potential precursors for the fabrication of advanced structural ceramics.

Progress in the use of silazane precursors to Si_3N_4 has mainly concentrated on the development of synthetic methods for preparing polymers with higher ceramic yields and improved selectivity to ceramic products [2]. Less attention has been given to the basic relationships between the chemical content and the structure of polymers, or the pyrolysis conditions, and the nature of the derived ceramic materials. Consequently, there are insufficient data concerning the chemical reactions and their kinetic and mechanistic pathways that occur during the thermal transformation of a well-defined polymer to a ceramic network. This information is critical for the design of advanced preceramics and better pyrolytic processes to achieve higher ceramic yields and purities.

This article presents some correlations between polysilazane chemical

2

compositions and structures and their derived ceramic products. It also shows

the feasibility of using transition metal catalysis [3] as a synthetic tool for

forming new precursors to Si_3N_4 with novel chemical, rheological, viscoelastic,

and pyrolytic properties. The precursors described here include a promising

polymer prototype based on the monomeric units $-[H_2SiNCH_3]-$ [4]. This family

of preceramic polymers has been further investigated for its pyrolytic

properties under a variety of thermolytic conditions, as will be described

elsewhere.

2. Background

Twenty years ago Chantrell and Popper envisioned the possibility of

converting tractable polymers* having an inorganic skeleton to ceramic

materials [5]. The interest in this approach has increased steadily in the

past ten years since the commercialization of polymer-derived silicon carbide

fibers [6] and binders [7]. It has been driven by the necessity to improve

the performance of ceramic materials for advanced applications. Wynne and Rice

have summarized the progress in this growing field and set a series of general

empirical rules that should be considered for the design of a proper ceramic

precursor [8]. These rules are based on experimental observations and logical

assumptions. An optimal polymer should have the following properties: (1)

high molecular weight--to reduce volatilization; (2) tractability

(meltability, malleability or solubility)--to apply the preceramics in the

---

* Historically, the definition of **polysilazane** is less restricted from that
of organic polymers as M_n values higher than 3000 daltons (a medium size
organic oligomer) are rarely known. In this article we use the definition of
polymer for all the preceramic products described by the related literature,
and for the nonvolatile products obtained after the dehydrocoupling catalysis.
The definition of oligomer is used for the description of volatile silazanes,
and for the oligomeric building blocks used in the catalytic polymerization
process.

desired shape before the pyrolytic process; (3) polymeric structure that is slightly branched or contains cages or rings--to decrease the polymer skeleton degradation; (4) the presence of latent chemical reactivity--to obtain thermosetting or curing properties; (5) low organic functional group content--to increase ceramic yields and avoid the production of undesired free carbon and carbide ceramics.

Other empirical rules are more specific to a certain type of ceramic material or application. For example, the presence of $Si-CH_3$ functional groups on polysilazanes consistently results in the production of a significant amount of SiC along with the Si_3N_4 when pyrolyzed under inert atmosphere [9]. Therefore, these groups are detrimental to the goal of producing SiC-free Si_3N_4. Furthermore, by analogy to organic polymers, linear-type preceramic polymers having number average molecular weights (M_n) of 20,000 to 50,000 daltons were predicted [10] to allow good fabrication of ceramic fibers. The high molecular weight is needed to increase the tenacity of the preceramic fibers. So far, this goal has not been achieved for any of the nitride precursors, though polymers having satisfied tenacity have been spinned to fibers as a result of other polymer properties [9, 11].

Some of the desired polymer properties are counterproductive to each other. Low organic group content [11] or excessive branching may cause the polymer to be intractable, labile, or very sensitive to air and moisture exposure [12]. A linear polymer having sufficient molecular weight may be fabricated into an excellent fiber, but it will melt or totally decompose during the pyrolysis if it is not made infusible prior to the thermolytic process [3a]. Therefore, the design of an optimal precursor requires a balance between versatile properties and specific demands for the individual application.

4

The common method for silazane synthesis is the ammonolysis (aminolysis) of halosilanes, which was first discovered more than sixty years ago [13]. In general, the ammonolysis products are either low molecular weight cyclomers (n=3-5), if dihalosilanes are used, or crosslinked and intractable polymers when tri- or tetrahalosilanes are introduced as reactants [12]. Recently, higher linear polymeric products having the general unit type $[R_2SiNR']_n$ have been synthesized by direct ammonolysis (aminolysis) methods [14]. However, the intensive research efforts in preceramic polysilazanes have been accompanied by the development of alternative synthetic methods. These methods use catalytic [9c,d,15] or high temperature reactions [9a,b,e-i,16] to convert in different pathways mono- and oligosilazanes to polymers that try to meet the rules set above.

The silazanes used in the following pyrolysis studies are the products of a catalytic approach to the synthesis of suitable silicon nitride precursors [3,4]. Transition-metal catalysts promote ring opening polymerization by which Si-N bonds are activated and a metathesis (rearrangement) reaction takes place to form new Si-N bonds:

$$x [R_2SiNH]_n \xleftrightarrow{\quad catalyst \quad} [R_2SiNH]_{xn} \qquad (1)$$

These catalysts can also successfully promote Si-N bond formation derived from dehydrocoupling Si-H with N-H bonds under relatively milder conditions, as in reaction (2).

$$n\ R_2SiH_2 + n\ R'NH_2 \xrightarrow{\quad catalyst \quad} n/x\ [R_2SiNR']_x + 2n\ H_2 \qquad (2)$$
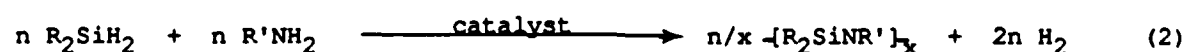
Catalytic dehydrocoupling can be used to produce various prototypes of polysilazanes from silane or oligosilazane building blocks. These polysilazane

5

precursors have a wide range of structural and chemical characteristics related to the structure and chemical reactivity of the starting reagents. The synthetic approach can thus be used as a tool to study the effects of variations in polysilazane chemistry on their pyrolytic properties. Some of these silazanes have excellent polymeric properties [17] and pyrolytic characteristics [18] for use as preceramic materials and are under investigation for binder [19], coating [20], and fiber [21] applications.

3. Experimental

3.1. General methods

All liquid silicon compounds were purchased from Petrarch System Inc. and were purified by distillation from CaH_2. Gases were purchased from Matheson Gas Products and ruthenium catalyst from Strem Chemicals, and these were generally used without further purification. Ammonia and monomethylamine used under atmospheric pressure were dried by passing through a KOH trap. Tetrahydrofuran and ethyl ether were purchased from Mallinckrodt and purified by distillation over sodium-benzoketyl complex under nitrogen.

3.2. Polymer characterization

Polymer product analyses are described elsewhere [3,17] and will not be discussed in this article. In general, [1]H- and [29]Si-nuclear magnetic resonance (NMR), gas chromatography (GC), gas chromatography-mass spectrometry (GC-MS), and infra-red (IR) techniques were used for chemical characterization. Vapor-phase osmometry (VPO), size exclusion chromatography (SEC), and rheometry were the analytical methods for the polymer property evaluations.

3.3. General catalytic procedure

All reactions were normally run in a magnetically stirred 45-mL Parr stainless steel reactor, equipped with pressure gauge and gas loading

6

inlet-outlet. Reactants (silanes and oligosilazanes) were added to the loaded catalyst under nitrogen in a dry box. The sealed reactor was heated in an oil bath controlled by thermocouple with an error limit of $\pm 2°C$. Whenever ammonia was used as a reagent, the reactor was pressurized to maximum (usually 80-90 psig); then the charged gas was allowed to dissolve in the solution. The procedure was repeated until saturation was reached, as determined by the absence of pressure drop. The reaction progress was monitored by the hydrogen pressure buildup at constant reaction temperature. The reactor was periodically cooled and depressurized to release the generated hydrogen and recharge the autoclave with ammonia.

3.4. Polymer synthesis

3.4.1. Si-Oligodiethylsilazane (ODES)

To 25 μmol of $Ru_3(CO)_{12}$ (16 mg) was added 20.0 mmol of diethylsilane (1.76 g). The solution was heated at 60°C under approximately 200 psi of ammonia. The reactor was recharged with NH_3 after 1 h and heated again for 2 h until gas evolution ceased. The starting reagent totally disappeared, and a series of linear and cyclooligomers was obtained and analyzed by GC and GC-MS.

3.4.2. Si-Polyphenylsilazane (PPS)

To 25 μmol of $Ru_3(CO)_{12}$ (16 mg) was added 10.0 g of phenylsilane, and the reactor was heated initially at 60°C, under approximately 200 psi of ammonia. The gas phase was replaced periodically with a fresh amount of ammonia and the reaction was carried on for 20 h; then the temperature was raised to 90°C. After 30 h, 5 mL of THF was added to decrease the solution viscosity. After 40 h; 8 mg of catalyst was added to enhance reactivity. THF was removed by vacuum evaporation at 60°C/200 μm.

3.4.3. Si-Polyhexylsilazane (PHS)

The reaction was run under the same quantities and initial conditions used for the PPS formation. After 23 h, the temperature was raised to 90°C;

7

after 35 h, an additional 16 mg of catalyst was added, followed by a second addition of 8 mg catalyst and 5 mL of THF after 44 h. The reaction was terminated after 56 h and solvent was evaporated by vacuum (60°C/200 μm).

3.4.4. N-Polymethylsilazanes (PNMS)

To 50 g N-oligomethylsilazane (ONMS; M_n = 1,100, M_w = 4,000, M_z = 13,100 daltons; Viscosity = 5 poise) was added 100 mg $Ru_3(CO)_{12}$, and the mixture was heated at 90°C in a magnetically stirred quartz reactor sealed under nitrogen The reaction was continued for 65 h and the evolved polymer was found to have M_n = 2300, M_w = 23,600, M_z = 128,000 daltons and a viscosity of 98 poise.

3.5. Pyrolysis studies

Bulk pyrolysis experiments were conducted under controlled conditions in a quartz tube connected by a manifold to several gas lines and a vacuum pump. The reaction tube was placed inside a lindberg horizontal tube furnace controlled by a Barber-Coleman 570 programmable controller. This experimental configuration allowed polymer pyrolyses to be carried out under a variety of atmospheres or mixtures of gases. Samples for bulk pyrolysis were loaded into quartz crucibles in a nitrogen dry box and transferred to the furnace. After several evacuation/purge cycles, the samples were heated with a linear ramping schedule under flowing nitrogen. Gas flow rates were typically 60 mL/min and the standard heating rate was 0.5°C/min. Samples were heated to 800°C and held at that temperature for 3 h.

Some polysilazane pyrolysis products were subsequently heated to 1600°C in a Centorr Associates high-temperature, controlled-atmosphere furnace. This furnace has a graphite heating element and is capable of generating gas pressures of 2000 kPa. Pyrolyzed material was placed in molybdenum crucibles and heated to 1600°C at ~10°C/min in a static nitrogen environment. Gas pressure was ~100 kPa at room temperature and increased to ~700 kPa at 1600°C.

8

The products of polysilazane pyrolysis and high temperature treatment were investigated by powder x-ray diffraction techniques for phase identification. Bulk chemical analyses for C, H, Si, N, and O were performed at Galbraith Laboratories of Knoxville, TN. Periodic duplicate analyses and analysis of commercial Si_3N_4 were also performed to corroborate the results.

To obtain more detailed information on the mechanisms of polymer pyrolysis, thermogravimetric analysis (TGA) experiments were performed. These experiments used a vertical clamshell furnace and a Cahn RG microbalance controlled by an Apple II Plus microcomputer. TGA experiments were performed under identical conditions of atmosphere and heat treatments as the bulk pyrolysis experiments. Sample masses of ~30 mg were loaded in quartz baskets and heated under flowing nitrogen. Mass determinations averaged from 300 measurements were collected every 4 minutes with an error of ± 50 μg at low temperatures and ± 75 μg at temperatures above ~600°C.

Several different mass spectrometry experiments were performed to determine the composition of fragments released during the conversion of polysilazane to ceramic material. This was necessary because the evolved fragments during the pyrolysis have a wide range of molecular weights and volatilities with different chemical interactions on chromatographic supports.

Two GC-MS systems were used for analyzing volatile decomposition compounds collected from vapors that were carried by the nitrogen flow and passed through a hexane solution trap at -78°C. One was a Ribermag R 10-10-C equipped with 5 m fused silica capillary column; the carrier gas was helium. This instrument is sensitive to compounds having more than 50 amu. The second was an LKB 9000 equipped with 2-m packed column with 4% carbowax 20 M on Carbopack B, 0.8% KOH. This system successfully detected the gaseous decomposition products.

For identifying heavy pyrolysis fragments, Knudsen cell mass

9

spectrometry was found to be an effective technique [22]. Polysilazane was loaded into a Knudsen cell, a small molybdenum cylindrical container with a very small orifice. The cell was placed in a high vacuum system with the orifice in line-of-sight with a mass spectrometer ion source and heated to high temperature. The gaseous fragments formed during pyrolysis eventually escaped through the orifice and were detected by the mass spectrometer. Because the cell was at high temperature, the heavy fragments could be detected before they condensed.

Pyrolysis/Field Ionization Mass Spectrometry (Py/FIMS) was also used for the detecting high molecular weight volatiles [23]. Approximately 50 µg of samples were introduced via a heated direct insertion probe, and the samples were heated gradually from room temperature to 500°C under high vacuum.
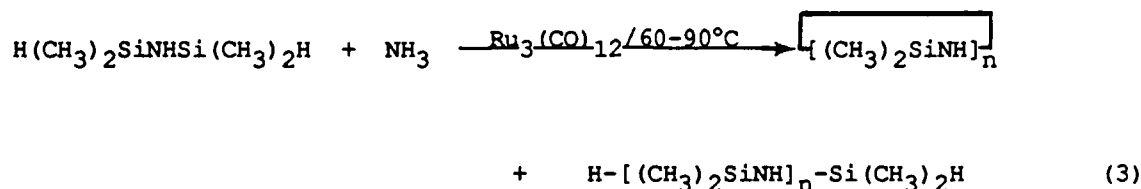
Lighter, more volatile decomposition products of polysilazane pyrolysis were identified using temperature-programmed-reaction (TPR) mass spectrometry. The polysilazane was heated in a quartz tube under flowing helium. The helium acted as a carrier gas that transported light pyrolysis fragments through a gas line to a mass spectrometer where these fragments could be identified. The gas line was heated to 150°C. The heavy, nonvolatile fragments of polysilazane pyrolysis, which condense rapidly at low temperatures, could not be detected by the TPR apparatus because of condensation on the walls of the gas line.

4. Results

Various types of oligo- and polysilazanes substituted on their silicon and nitrogen skeleton atoms with different organic groups were synthesized by the transition-metal catalytic dehydrocoupling reaction [3,4]. Their pyrolytic behavior and the evolution of their ceramic products were examined; the results are discussed below.
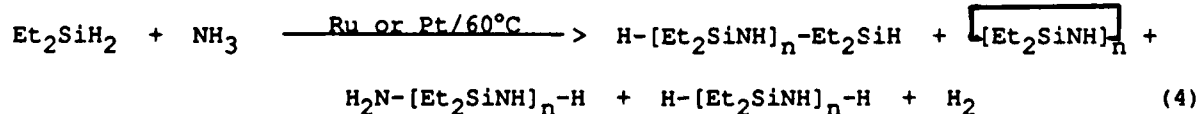
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4.1. Si-Dialkylsilazanes

Tetramethyldisilazane was reacted with ammonia in the presence of transition metal catalyst to produce a mixture of cyclic and linear oligomers and polymers [3a,b]:

$$H(CH_3)_2SiNHSi(CH_3)_2H \ + \ NH_3 \ \xrightarrow{\ Ru_3(CO)_{12}/60-90^\circ C\ } \ [(CH_3)_2SiNH]_n$$

$$+ \quad H-[(CH_3)_2SiNH]_n-Si(CH_3)_2H \qquad (3)$$

The ratio of cyclomers to linear oligomers was dependent on the catalyst type and the reaction conditions. After distillation of the volatile oligomers at 150-180°C under a vacuum of 40 Pa (300 μm), the remaining polymeric fraction ~20 wt% was analyzed as linear 1,1-dimethylpolysilazane(PDMS) with number average (M_n), weight average (M_w), and Z average (M_z) molecular weight values of 2,000, 9,600, and 28,100 daltons, respectively.

Pyrolysis of this polymer yields negligible amounts of ceramic products. The TGA results (Figure 1) indicate that weight loss is fairly continuous between 150-500°C, at which point the rate of decomposition is slightly enhanced. Because the polymeric fraction is the nonvolatile residue (180°C/40 Pa) of reaction (3), polymer volatility cannot account for the low ceramic yield. Such behavior is explained only by a continuous cleavage of Si-N backbone, enhanced by parallel Si-C bond cleavage that starts above 450°C.

The catalytic dehydrocoupling of diethylsilane with ammonia shown in Reaction (4) produces a similar mixture of oligomers [3a,b].
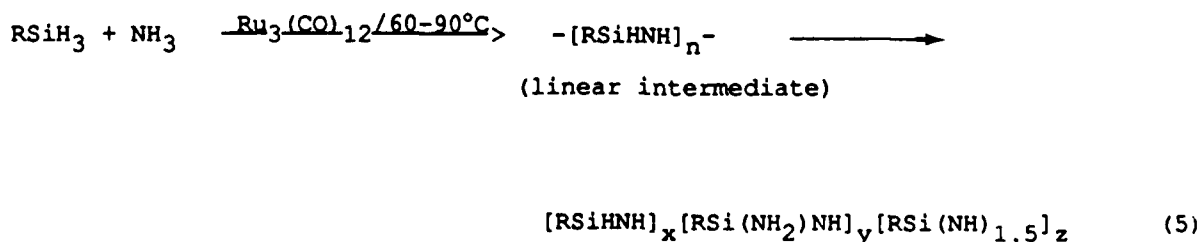
$$Et_2SiH_2 \ + \ NH_3 \ \xrightarrow{\ Ru\ or\ Pt/60^\circ C\ } \ H-[Et_2SiNH]_n-Et_2SiH \ + \ [Et_2SiNH]_n \ +$$

$$H_2N-[Et_2SiNH]_n-H \ + \ H-[Et_2SiNH]_n-H \ + \ H_2 \qquad (4)$$

The oligodiethylsilazane (ODES) products contain only low molecular weight cyclic and linear oligomers (M_n = 300-400 daltons). Pyrolysis of this material gives a negligible ceramic yield. This is not unexpected, given that vacuum distillation provides almost no nonvolatile materials.

4.2. Si-Monosubstituted Polysilazanes

The use of monosubstituted silanes in the catalytic dehydrocoupling reactions with ammonia adds another reactive site on each silicon atom. This third Si-H bond causes the formation of two- and three-dimensional polymers. The potential increase in latent reactivity of the resultant polymer (Si-H and Si-NH_2 functional groups) allows for a controlled degree of crosslinking. The higher dimensional structure of crosslinked polymers should suppress the decomposition reaction leading to volatiles and result in higher ceramic yields. The choice of the substituted organic group should affect the polymerization kinetics and the regio- or the chemioselectivity of the polymer growth when a multifunctional step-reaction polymerization is available. These groups also have a major impact on the polymer properties as well as on the derived ceramic yields and compositions.

Different monosubstituted silanes [$RSiH_3$ where R is phenyl (C_6H_5), hexyl (C_6H_{13}) or ethyl (C_2H_5) group] were reacted catalytically with ammonia, Reaction (5), to form bridged, branched, or ring type polymeric products after initial

$$RSiH_3 + NH_3 \xrightarrow{Ru_3(CO)_{12}/60-90°C} -[RSiHNH]_n- \longrightarrow$$
$$\text{(linear intermediate)}$$

$$[RSiHNH]_x[RSi(NH_2)NH]_y[RSi(NH)_{1.5}]_z \qquad (5)$$

12

formation of linear oligomeric intermediates.

The physical and the pyrolytic properties of polymers synthesized by
reaction (5) are strongly dependent on the chemical properties and behavior of
the substituted organic groups. Linear polymerization and the subsequent
bridging or crosslinking processes are strongly influenced by steric effects.
The ethylsilane reaction produces a crosslinked, infusible soft rubber after
only 6 h at 60°C. Meanwhile, Si-polyphenylsilazane (PPS) is still a liquid
after 30 h at 60°C (M_n~850 daltons), but transforms to a meltable solid (M_n ~
1200 daltons) when the temperature is raised to 90°C. The Si-polyhexylsilazane
(PHS), also a liquid after 30 h at 60°C, does not solidify after an additional
26 h at 90°C despite having M_n~2200 daltons, nearly twice that of the phenyl
analog. Clearly, the steric bulk of the phenyl and hexyl groups inhibit
extensive crosslinking even after longer reaction periods and at higher final
temperature.

4.2.1. Pyrolysis Studies

The effects of the organic substituents on polymer molecular weight,
ceramic yields and pyrolysis products are shown in Table I. The high ceramic
yields obtained with the polyphenylsilazane precursors result from extensive
carbon incorporation. The calculation of the partial weight loss of elemets
during pyrolysis reveals that gaseous mixture arising in the pyrolysis of the
50-h phenylsilazane are mainly organic. Small amounts of nitrogen containing
compounds are also released but loss of silicon content is not observed. The
20-h phenylsilazane, which has an excess of Si relative to Si_3N_4 stoichiometry,
apparently does lose silicon during pyrolysis because of the presence of
volatile silicon species coinciding with direct skeleton fragmentation. This
difference demonstrates the necessity of crosslinking or branching to achieve

13

good ceramic yields.

The hexylsilazane pyrolysis products have lower carbon contents than those of the phenyl analog, which can partially explain their relative low ceramic yields. The low ceramic yields given by the 56-h hexylsilazane are also attributed to the loss of compounds containing ~ 6 wt% Si and ~ 10 wt% N. The release of silicon and nitrogen contained compounds is even more pronounced for the 30-h oligomeric mixture that contains remains of the volatile hexylsilane, low molecular weight oligomers, and linear species that can be thermally degraded.

Examination of the chemical composition of the pyrolysis products as shown in Table II demonstrates that polymeric precursors of the same type with higher nitrogen contents have correspondingly higher N:Si mole ratios in the final material. For both hexyl- and phenylsilazanes, the more highly polymerized material is transformed to a ceramic product with N:Si ratios close to stoichiometric Si_3N_4. It is clear that all materials produced from polymer pyrolysis to 800°C have hydrogen present in significant concentrations. The high mole ratios of hydrogen cannot be accounted in terms of C-H bonds alone, based on the residual carbon, and point to the presence of Si-H and/or N-H bonded species in the pyrolysis product [11c].

The inorganic materials derived from the pyrolysis of the hexyl and the phenyl substitueted polysilazanes were heated further to 1600°C. This results in the crystallization of α- and ß-Si_3N_4 from the previously amorphous pyrolysis products. Changes in chemical composition during the high temperature treatment include significant decrease in the carbon and hydrogen content. Stoichiometric calculations indicate that only small amounts of SiC (~5 wt%) can possibly be produced at 1600°C. This observation is supported by the absence of SiC in the XRD pattern.

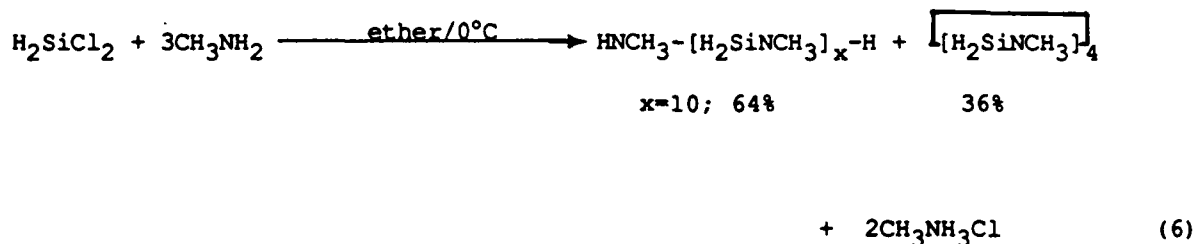TGA studies of the crosslinked 50-h phenylsilazane and 56-h

14

hexylsilazane (Figure 2) reveal that both are stable to 250°C. Only small mass fractions are lost below 400°C, the range in which retroversion and redistribution reactions of the silicon-nitrogen skeleton are usually detected (see discussion). The significant differences in thermal reactivity between the phenyl and the hexyl polysilazanes are found in the temperature region between 400 and 550°C. Si-C bond cleavage for the hexyl group is rapid above 400°C and indicates lower kinetic or thermodynamic barriers. The phenyl group is cleaved slowly, suggesting different chemical reactivity; and probably involves carbon-carbon interactions that generate the high carbon content.

The third TGA profile in Figure 2 tracks the pyrolytic behavior of the linear, low molecular weight 30-h hexylsilazane. The initial weight loss results from volatilization of unreacted hexylsilane (boiling point of 114°C) that is present in a concentration of ~12 mol% as determined by NMR and GPC. In contrast to the 56-h sample, there is only one degradation step at the region over 300°C.

4.3. N-polymethylsilazane (PNMS)

Polymer growth by coupling of linear oligosilazanes through chain extension, branching, or crosslinking is another potential advantage provided by the catalytic dehydrocoupling process. According to the general empirical rules described above, an optimal Si_3N_4 precursor should be a tractable, nonvolatile silazane that is not substituted by $Si-CH_3$ or larger organic groups but contains functional groups with latent reactivity. In contrast, it has already been demonstrated that Si-H bonds may provide the desired latent reactivity, allowing the precursor to thermoset during pyrolysis. oligo-N-methylsilazane, $HNCH_3-[H_2SiNCH_3]_n-H$ (ONMS), seems to be an ideal candidate that combines many of the optimal precursor properties together with the potential for extension by the catalytic dehydrocoupling reaction. The

15

oligomer, first reported by Seyferth and Wiseman [3c], was produced by reacting dichlorosilane with methylamine:

$$H_2SiCl_2 + 3CH_3NH_2 \xrightarrow{\text{ether/0°C}} HNCH_3\text{-}[H_2SiNCH_3]_x\text{-}H + \overline{[H_2SiNCH_3]_4}$$

$$x=10; \ 64\% \qquad\qquad 36\%$$

$$+ \ 2CH_3NH_3Cl \qquad\qquad (6)$$

A considerable fraction of cyclotetramer was obtained that did not contribute to the ceramic yield because of its volatility. The linear oligomer was isolated by distillation and gave a pyrolysis yield of 39%.

The Si-H and Si-NRH functional groups of ONMS are able to either dehydrocouple in the presence of catalyst under mild conditions or supply thermosetting reactivity at elevated temperatures. Higher oligomer ($x = 17$-21) was produced by changing the aminolysis reaction conditions, and the volatile fraction was reduced to 10-15 wt%. This latter oligomer was catalytically polymerized using $Ru_3(CO)_{12}$ under a variety of conditions, and the pyrolysis properties of the resulting polymers were examined. Variations in temperature, the amount and type of catalyst, and the use of solvents were found to affect the polymerization process [17,21]. During the reaction period, the degree of polymerization increased, reflected by values of $M_n = 2000$-2800 daltons, $M_w = 20,000$-$50,000$ daltons, and $M_z = 80,000$-$500,000$ daltons for the liquid polymer before transformation to a gel. Figure 3 shows typical Size Exclusion Chromatography (SEC) results for a catalytic polymerization product, PNMS, in comparison with the initial oligomeric reactant, ONMS. During the process, viscosity increased dramatically from 1-5 poise up to 4000-6000 poise. The polymers at the higher viscosities exhibited non-newtonian behavior, yet maintained their tractability.

16

4.3.1. Pyrolytic Characteristics

To evaluate PNMS as a ceramic precursor and study the thermolytic steps of pyrolysis, we performed a series of bulk pyrolysis, TGA, and powder XRD experiments on catalytically produced polymers and compared the results with those of similar experiments on the initial oligomer, ONMS. The ceramic yields are shown in Table III along with the results of elemental analysis. These data disclose a series of significant findings. First and foremost, the ceramic yields of the catalytically treated polymer are substantially higher than the untreated ones, but the ceramic compositions are almost the same for each of the environmental conditions. Therefore, although catalytic chain extension or crosslinking increases the ceramic yields, the monomer molecular structure controls the ceramic compositions. As determined from Table IV the high hydrogen content found in the pyrolysis products is partially associated with the inorganic Si-H and N-H remaining and not with the carbon residue alone.

Figure 4 exhibits TGA plots of ONMS and PNMS pyrolyzed under nitrogen. Both plots demonstrate similar thermolytic behavior: (a) a moderate decrease in between 100-230°C; (b) a faster decomposition between 230-350°C; (c) a plateau in the range of 350-500°C; and (d) further decomposition in between 500-600°C After the last stage no further decomposition is observed up to 900°C. These pyrolysis steps indicate different chemical processes that are further characterized by mass spectrometry (MS) experiments described below. The major difference in weight loss behavior between ONMS and PNMS occurs in the temperature range in between 100-350°C. The final weight loss segment shows exactly the same proportional degradation for both.

To obtain the full effect of the catalytic process, the polymerization reaction must proceed over a significant period of time. This is demonstrated in Table III by run 4, where the oligomer is pyrolyzed in the presence of

17

catalyst without a preliminary catalytic treatment. Neither the ceramic yield nor the composition of the pyrolysis product were affected relative to the oligomer pyrolyzed without the catalyst present.

Analysis of the material treated at 1600°C shows that the N:Si ratio no reaches the stoichiometry of crystalline silicon nitride. This coincides with the appearance of α- and $\ast$-Si_3N_4 in the XRD pattern. No evidence for SiC is seen from XRD. The H:Si mol ratio decreases to 0.05 and the residual hydrogen may be associated with ceramic carbon or moisture impurities. Comparison between the 800°C and the 1600°C results of both ONMS and PNMS pyrolyzed under nitrogen relates the additional weight loss (~19 wt%) above 800°C to the decrease in excess carbon, hydrogen, and nitrogen in the amorphous products.

4.3.2. Mass Spectrometry studies

Analytical evaluation of the thermolytic behavior detected by the TGA experiments is critical to understanding the chemical mechanisms that occur during the heating process. Mass spectrometric (MS) studies of the evolved volatile products during pyrolysis can be correlated to the TGA results and provide some explanation of the weight loss mechanisms. However, because of the wide range of molecular weights and chemical species evolved during pyrolysis, not all volatile products can be followed simultaneously by the same instrumentation. Furthermore, gas chromatography-mass spectroscopy (GC-MS) methods require different columns to cover a range of products having different volatility, polarity, or sensitivity toward different column packing. Therefore, a variety of MS instruments were used so as to overlap the whole spectrum. The techniques included high vacuum instrumentation for nonvolatile fragments, helium atmosphere equipment for the very low molecular weight compounds, and two GC-MS sets for low and high molecular weights. The combined results are qualitatively summarized in Table V and can be easily correlated to

18

the different areas of reactivity observed by the TGA plots.

The proposed volatile silazane structures include cyclomers and linear and bridged oligomers, as illustrated in Scheme I. The three different decomposition stages shown by TGA are corroborated by the MS results. The first stage includes the generation of oligosilazanes, which continues into the second. The second stage is characterized by the evolution of SiH_4 and CH_3NH_2. The decomposition above 500°C involves carbon release together with chemical redistribution, a condensation of the organic residue that probably leads to the carbonization process.
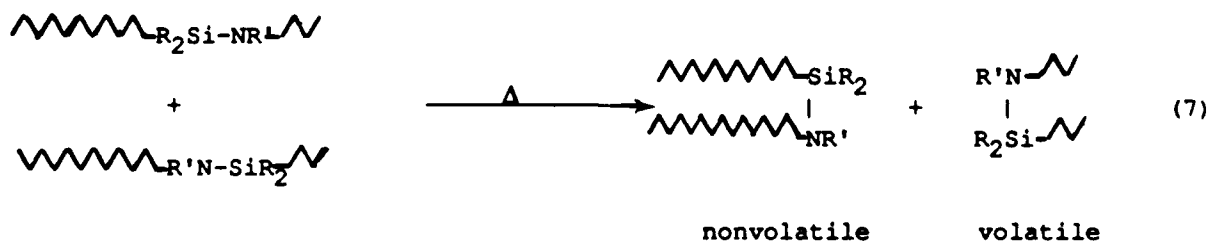
5. Discussion

The pyrolysis results primarily demonstrate the strong relationship between the nature of the preceramic silazane and the pyrolysis-derived products. The functional groups that are bound to the Si-N based skeleton and isomeric polymer structures dominate the ceramic yields and chemical compositions of the pyrolyzed products. In rationalizing the results of this investigation, hypothetical mechanisms are suggested with respect to current knowledge about thermolysis chemistry in general and polysilazane pyrolysis in particular. The postulated mechanisms have not been shown to be directly applicable to the conversion of polysilazanes to ceramic products.

5.1. Dependency on polymer structure

From our own studies and those of others [9,11,14,16], it is apparent that polymer structure is a major factor in determining the ceramic yields. The pyrolysis of dimethylpolysilazane (PDMS) confirms the observation that linear polymers without latent reactivity are unfavorable preceramics. This is further corroborated by the results on the pyrolysis of the linear, low-molecular weight PHS, PPS, and ONMS aliquots. In comparison, the

19

relatively branched, crosslinked, or ring type (necklace) polymers, which were developed after further catalytic treatment of each oligomer type, exhibited conversion to ceramics with higher yields. These results actually confirm the general observation for the best preceramics available today; namely that all consist of necklace, sheet, or branched type structures. The presence of a crosslinked structure or the capability of a polymer to further crosslink at low temperatures retards the thermolytic retroversion reaction that causes the splitting out of volatile cyclomers from the polymer skeleton. This phenomenon is regarded as a universal observation [8] and has been repeatedly reported to occur during pyrolysis of both organic and preceramic polymers. Conversely, the retroversion reaction is promoted by the flexibility of any given polysilazane at temperatures between 200 to 450°C [9c,d,e-k,11,14]. The retroversion reaction competes kinetically with the crosslinking process. Therefore, any factors that constrain the flexibility (e.g. crosslinking, branching, rings, cages and bulk organic groups) or increase the latent reactivity of the polymer will result in higher ceramic yields [8].

The retroversion reaction is generally a metathetical rearrangement, as illustrated in Reaction (7). Interaction between the nitrogen lone pair

$$ \text{\textasciitilde}R_2Si-NR\text{\textasciitilde} $$
$$ + \quad \xrightarrow{\Delta} \quad \text{\textasciitilde}SiR_2 \quad + \quad R'N\text{\textasciitilde} \qquad (7) $$
$$ \text{\textasciitilde}R'N-SiR_2\text{\textasciitilde} \qquad \qquad \text{\textasciitilde}NR' \qquad R_2Si\text{\textasciitilde} $$

nonvolatile   volatile

of electrons and the empty d-orbitals of the silicon is suggested to form a penta - coordinated silicon followed by redistribution of the nitrogen-silicon bonds. The interacting groups may belong to the same or different polymer chains. If the same chain loops back on itself, then oligocyclomers split out

20

from the linear polymer and cause the degradation.

The MS patterns observed during the pyrolysis of PNMS in the temperature ranges 100-230°C and 230-350°C further support the retroversion assumption. This is implied by (a) the appearance of evolved silazanes with masses of 265 and 322 amu within the two different TGA ranges, (b) the detection of the more volatile silazane (177 amu) at the higher temperature range, and (c) the formation of cyclic and bicyclic (bridged) volatile silazanes.

The release of methylamine and silane at temperatures above 250°C suggests other rearrangement pathways that lead to crosslinking process. The formation of amines (or ammonia) and the rearrangement of hydrides around the silicon atoms are regularly observed among the volatiles generated during pyrolysis of polysilazanes [9,11,12,16]. Amine release may result via condensation of two amine groups ($-R_2Si-NHR$; R=H, organic group, silyl group), as exemplified by Reaction (8). This reaction is actually the driving force

$$2 \ R_3Si-NHR' \xrightarrow{\Delta} R_3Si-NR'-SiR_3 \ + \ R'NH_2 \qquad (8)$$
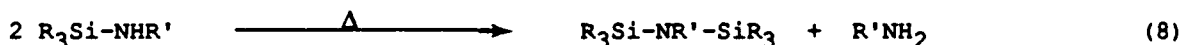
for the condensation-polymerization type reaction developed by Verbeek and Winter in which multiaminosilane monomers are successfully condensed to preceramic silazane resins [9a,b,16]. The thermal replacement of one silyl-amine group with another is known also as reamination [24] and may occur even at relatively low temperature in the presence of catalyst.

Reaction (9) describes a possible mechanism for the degradation of

$$2 \ R'NH-R_2Si-H \xrightarrow{\Delta} R'NH-R_2Si-NHR' \ + \ R_2SiH_2 \qquad (9)$$
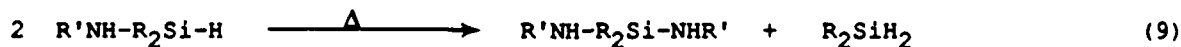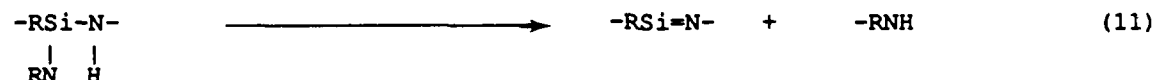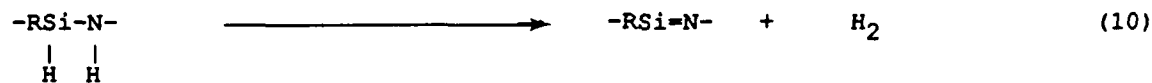
silanes at elevated temperatures [25], similar to the amine rearrangement. Both reactions (8) and (9) are responsible for increasing the crosslinking
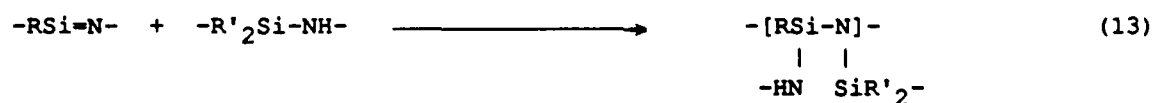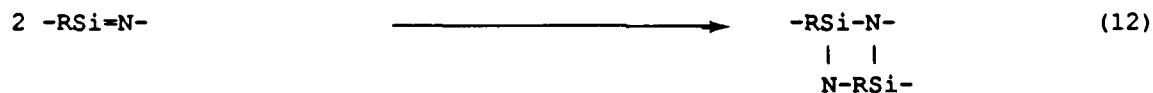
level.

Another hypothetical pathway for crosslinking process via silylimine intermediates can be postulated if silicon-nitrogen double bond can be formed as shown in Reactions (10) and (11). Silylimines will spontaneously couple

$$-RSi-N- \quad\xrightarrow{\hspace{4cm}}\quad -RSi=N- \;+\; H_2 \qquad (10)$$
$$\begin{array}{cc} | & | \\ H & H \end{array}$$

$$-RSi-N- \quad\xrightarrow{\hspace{4cm}}\quad -RSi=N- \;+\; -RNH \qquad (11)$$
$$\begin{array}{cc} | & | \\ RN & H \end{array}$$

with a second silylimine species or will insert into a silicon-nitrogen bond [26]:

$$2 \; -RSi=N- \quad\xrightarrow{\hspace{4cm}}\quad -RSi-N- \qquad (12)$$
$$\begin{array}{cc} | & | \\ N & -RSi- \end{array}$$

$$-RSi=N- \;+\; -R'_2Si-NH- \quad\xrightarrow{\hspace{3cm}}\quad -[RSi-N]- \qquad (13)$$
$$\begin{array}{cc} | & | \\ -HN & SiR'_2- \end{array}$$

5.2. Influence of organic functional groups

5.2.1. Ceramic compositions

The chemical structure of the monomeric unit primarily controls the development of ceramic compositions. Elemental analyses of ceramic products derived from N-methylsilazanes having different molecular weights and limited structural changes reveal almost identical chemical content regardless of the degree of polymerization. In contrast, different aliquots taken during the formation of both PPS and PHS show a direct relation between nitrogen-enriched polymers and higher nitrogen-to-silicon mol ratio in the ceramic products. Consequently, species containing Si-C bonds can be essentially eliminated from

22

the ceramic compositions in spite of the high carbon content.

As expected, different organic substituents on the polymer result in the formation of various carbon and carbide species as a consequence of their individual chemical reactivity. In related studies, organo substituted polysilazanes were pyrolyzed to nitrogen-deficient and carbon-rich products that were suggested to include SiC [9,11,14,16]. This postulate was rationalized by the fact that further heating above 1500°C indeed led to the transformation of the amorphous products to mixtures of Si_3N_4 and SiC crystallites. Explanations for SiC formation involved either (1) excessive Si-C bond content on the original polymer, which directly causes the carbide formation, or (2) the high temperature (>1450°C). Reaction (14) is

$$Si_3N_4 \quad + \quad C \quad \xrightarrow{\quad >1450°C \quad} \quad SiC \quad + \quad N_2 \qquad (14)$$

thermodynamically favored and heterogeneous mixtures of silicon nitride and carbon do react to form silicon carbide above 1450°C [27].

The polysilazanes pyrolyzed in this research demonstrate that neither the polymer Si-C bonds nor the development of ceramic carbon in the product mixture determinately cause the formation of silicon carbide. The hexyl and phenyl groups used in the present investigation are much larger than the methyl substituents, and especially the phenyl ones can be easily condensed to graphitic type products [28]. The PPS (50-h) derived product (800°C) contains excess nitrogen relative to stochiometric silicon nitride regardless of the large excess of ceramic carbon, whereas the PHS product has nitrogen-silicon mole ratio close to that of crystalline silicon nitride. The small silicon excess in the latter case is probably a result of minor amounts of Si-C, Si-H or Si-Si bonds. Further heating of both materials from 800°C to 1600°C leads to further carbon release. The nitrogen-to-silicon mole ratio is very close

23

to that of silicon nitride, coincident with possible presence of 4-6 wt% silicon carbide that were estimated by mass calculation. There is no evidence for crystalline carbides in the XRD spectra, which contains only a mixture of α- and β- Si_3N_4.

Similar characteristics are found for PNMS-derived ceramics, where a carbon fraction of 17-20 wt% is consistently produced. Again, the excess nitrogen prevents the formation of Si-C bonded species and high temperature treatment (1600°C) results in further reduction of the carbon content and adjustment of the nitrogen-to-silicon stoichiometry closer to that of Si_3N_4, confirmed by the appearance of mainly α-phase crystallite pattern in XRD.

The chemical reactivity of the N-methyl groups (N-C and C-H bond cleavage versus C-C bond formation) is observed at the temperature region of 500-600°C, somewhat lower than found regularly for Si-methyl substituents [11]. The difference is rationalized by the respectively lower bond dissociation energy of $N-CH_3$ bonds compared with $Si-CH_3$ [29]. Hydrocarbon compound polymerization and deposition as ceramic carbon should occur at the same temperature, probably by interactions inside the solid lattice and not in the gas phase. The latter demands higher temperatures than described here [28]. Therefore, the reactivity of the organic groups toward the above processes should be enhanced by their bonding to nitrogen or silicon atoms inside the solid lattice. Radical species generated by C-H and N-C homolytic bond dissociation are proposed as hypothetical initiators for carbonization and carburization processes. Such mechanisms were assumed for the Si-methyl group activity in the thermal conversion of polymetylsilanes to polycarbosilanes followed by the formation of SiC at elevated temperatures [30].

Longer alkyl groups than methyl should react differently during the thermolysis process. The residual carbon content of the PHS-derived materials

24

This discrepancy can be understood by the lower energy of activation required for the Si-C bond cleavage of this longer alkyl group relative to methyl. Metal-alkyl bonds are subject to a ß- elimination mechanism [31], if the alkyl group contains more than one carbon, as illustrated in Reaction (15). Indeed,

$$M-CH_2CH_2R \xrightarrow{\Delta} M-H + CH_2=CHR \qquad (15)$$

the TGA results of PHS suggest carbon content release at 450°C--approximately 100-150°C lower than needed for Si-CH$_3$ bond activation.

The TGA plots of the analogous phenyl-substituted polymers reveal Si-C bond activation at temperatures as low as 300°C. The ß-elimination mechanism is not possible for aromatic rings, but stable radical formation may ease the Si-C bond cleavage. Simultaneously, the phenyl groups can react with each other inside the solid lattice to form fused graphite-like ceramic materials [28].

The contradiction between the present results and those found in the current literature about the formation of SiC species is probably a result of using different polymer substituents. The related studies consist of pyrolyzing Si-CH$_3$ substituted polymers [9,11,14,16]. The methyl groups may be responsible to thermal formation of Si-CH$_2$-Si intermediate network in a mechanism close to that obtained during polysilane-to-polycarbosilane conversion [30]. Consequently, those intermediates will be thermolyzed to SiC patterns.

5.2.2. Ceramic yields

A secondary effect on the ceramic yields is attributed to the chemical behavior of the hydrocarbon substituents. It can be speculated that ceramic yields are either increased due to potential carbonization processes, or

decreased if high-molecular weight substituents are cleaved completely and released to the gas phase. Additional specific reactivity of substituents may also affect the ceramic yields. For example, silicon-dimethyl substituted silazanes are totally decomposed even if the polymer has a necklace structure [32] or is a crosslinked polymer [14b] rather than the linear structure described in this article.

Replacement of at least one silicon-organic substituent by hydrogen leads to moderate ceramic yields even for low molecular weight and linear oligomers [e.g., PHS (30-h), PPS (20-h) and ONMS]. The Si-H groups supply latent reactivity to thermoset the polymer by crosslinking process. Indeed, other linear polyhydridosilazanes developed recently such as $[CH_3SiHNH]_{n/2}[CH_3SiHNCH_3]_{n/2}$ [14b] and $[CH_3SiHNH]_n$ [14a] demonstrate similar pyrolytic behavior (ceramic yields of ~ 40 wt%). According to the literature, latent reactivity can be provided by an excess of aminic sites (Si-NH$_2$) [33] or (-NH-) groups on the main chain of a totally stripped off silazane ($[SiH_2NH]_n$) [11]. Both result in higher crosslinking by reamination-condensation reactions even at low as room temperature.

The inhibition of retroversion reactions is another secondary effect caused by the polymer substituents. Bulky organic groups induce polymer conformation and may suppress its capability to loop back and form reactive interactions with itself. For example, the 50-h PPS aliquot is pyrolyzed without any silicon deficiency, and the hexyl analog reveals only minor skeleton decomposition.

5.3. Amorphous ceramic structures and reactivities

The structural arrangement and chemical reactivity of polymer-derived amorphous ceramics is one of the most intriguing questions in this field of

26

research. Currently, the hydrogen content has usually been neglected when elemental analyses were used for predicting Si_3N_4, SiC, and C mol ratios in the product compositions. Yet, evidence shows that amorphous materials at 900-1100°C still contain Si-H, N-H, and C-Si-N bonds [11c,12]. The consistent lack of XRD pattern at this temperature range points out that the structures are random and disordered. Therefore, the above calculation procedure can be justified only for a preliminary estimation of the nitrogen excess or deficit, which allows us to predict the potential buildup of silicon or silicon carbide moieties if further heating takes place. The expression of the polymer-derived, amorphous ceramics as a mixture of crystalline ceramics (e.g. Si_3N_4, SiC, etc.) is probably incorrect. The reduction in hydrogen content coincides with the nitrogen-to-silicon ratio adjustment at 1600°C and the appearance of a crystalline pattern in the XRD spectra, which reinforces the above statement.

6. Conclusions

The results discussed above clearly demonstrate the critical relationship between the polymer chemical content and structure and the development of the pyrolysis products. Organic substituents have a variety of decomposition pathways that results in materials with a wide range of carbon contents. Functional groups that provide latent reactivity can compensate for undesired molecular flexibility in the ceramic yields. These factors are important for better design and tailoring of superior ceramic precursors. Future development in understanding the various thermal mechanisms that occur during the pyrolysis process will also result in improved chemical and pyrolytical processes with increased ceramic yields and decreased impurities.

27

Acknowledgements

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Captions

Figure 1:   The TGA profile of 1,1-polydimethylsilazane (PDMS)

Figure 2:   The TGA profiles of (a) PPS (50-h), (b) PHS (30-h) and (c) PHS
            (56-h)

Figure 3:   The SEC chromatograms of ONMS and PNMS (65-h)

Figure 4:   The TGA profiles of ONMS versus PNMS under the same inert pyrolytic
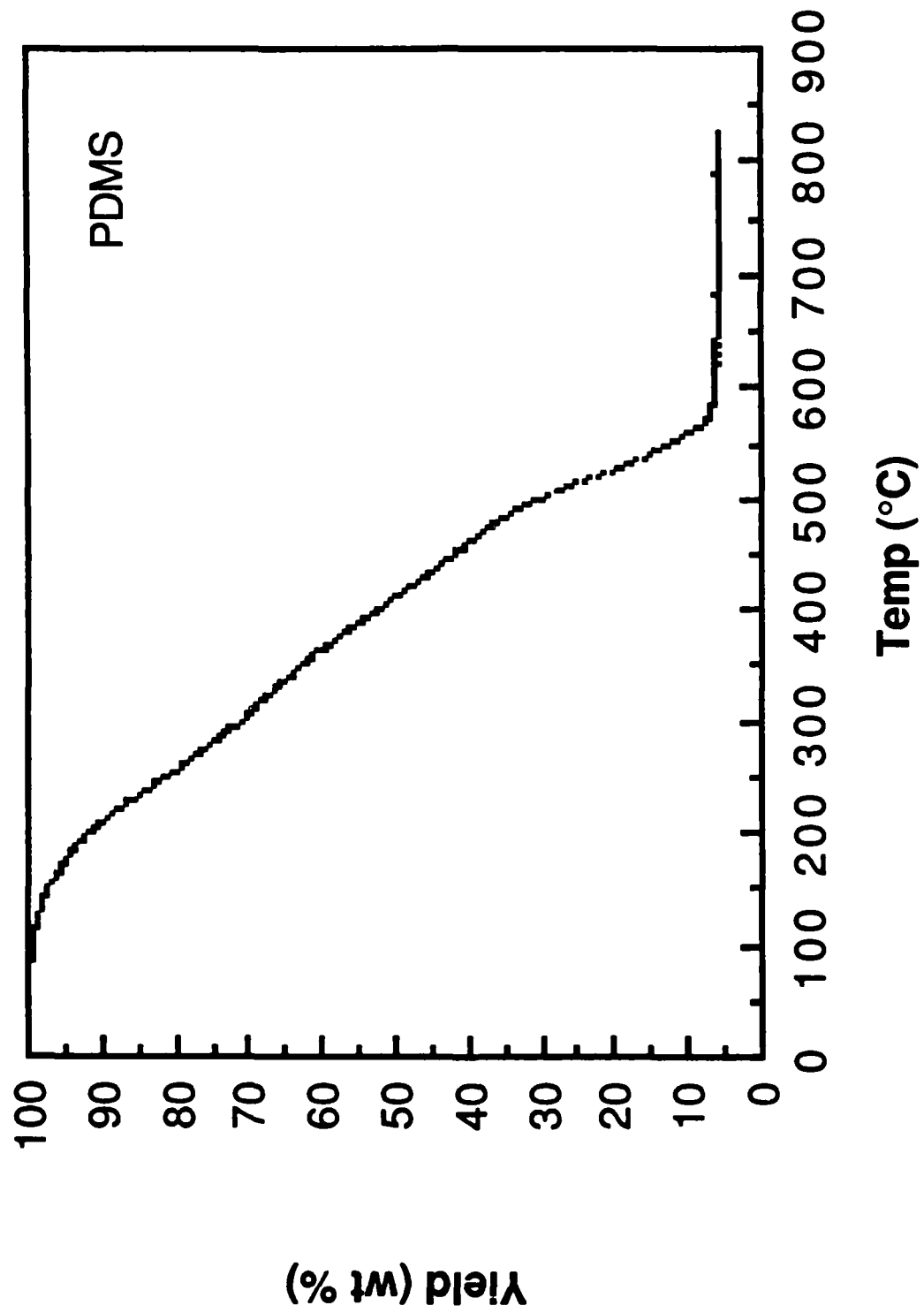   conditions

Table I: Polymer and pyrolytic properties of PPS and PHS aliquots

Table II: Chemical compositions of PPS and PHS aliquots and their derived
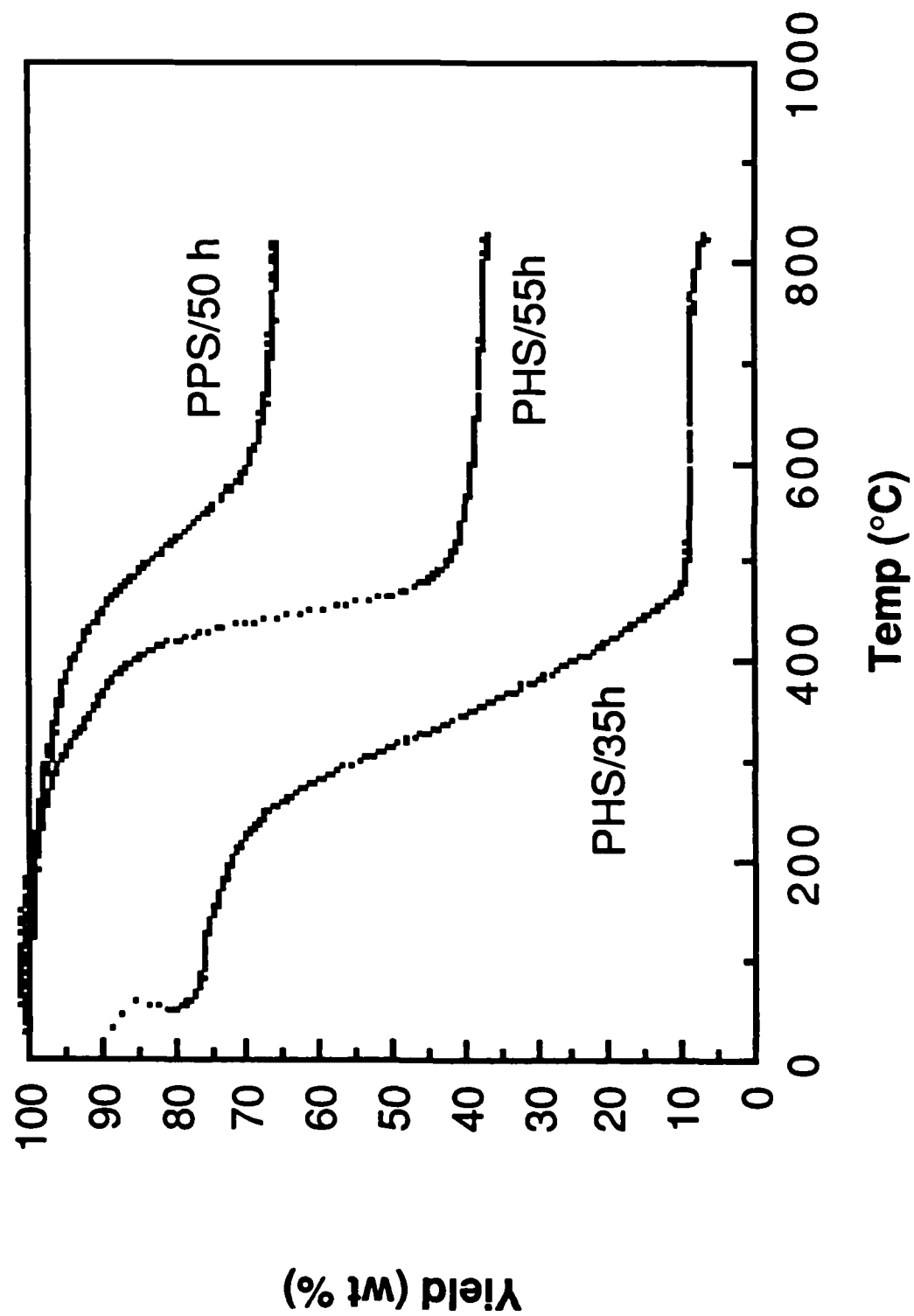   ceramic products

Table III: Pyrolytic results of ONMS and PNMS under various conditions

Table IV: Chemical compositions of ONMS and PNMS and their derived ceramic
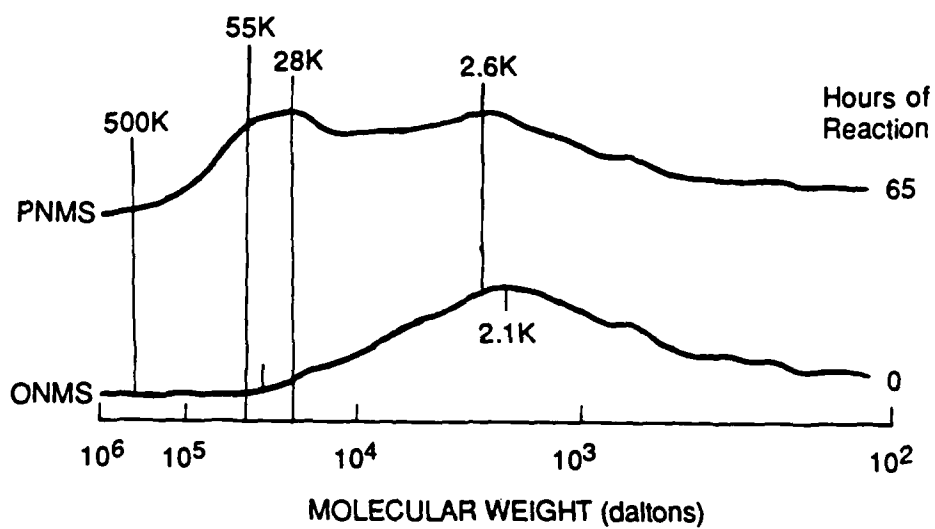   products.

Table V: Mass-spectrometry analysis of volatiles generated during the
            pyrolysis process of PNMS

Scheme I: Proposed structures of volatile silazanes released from PNMS
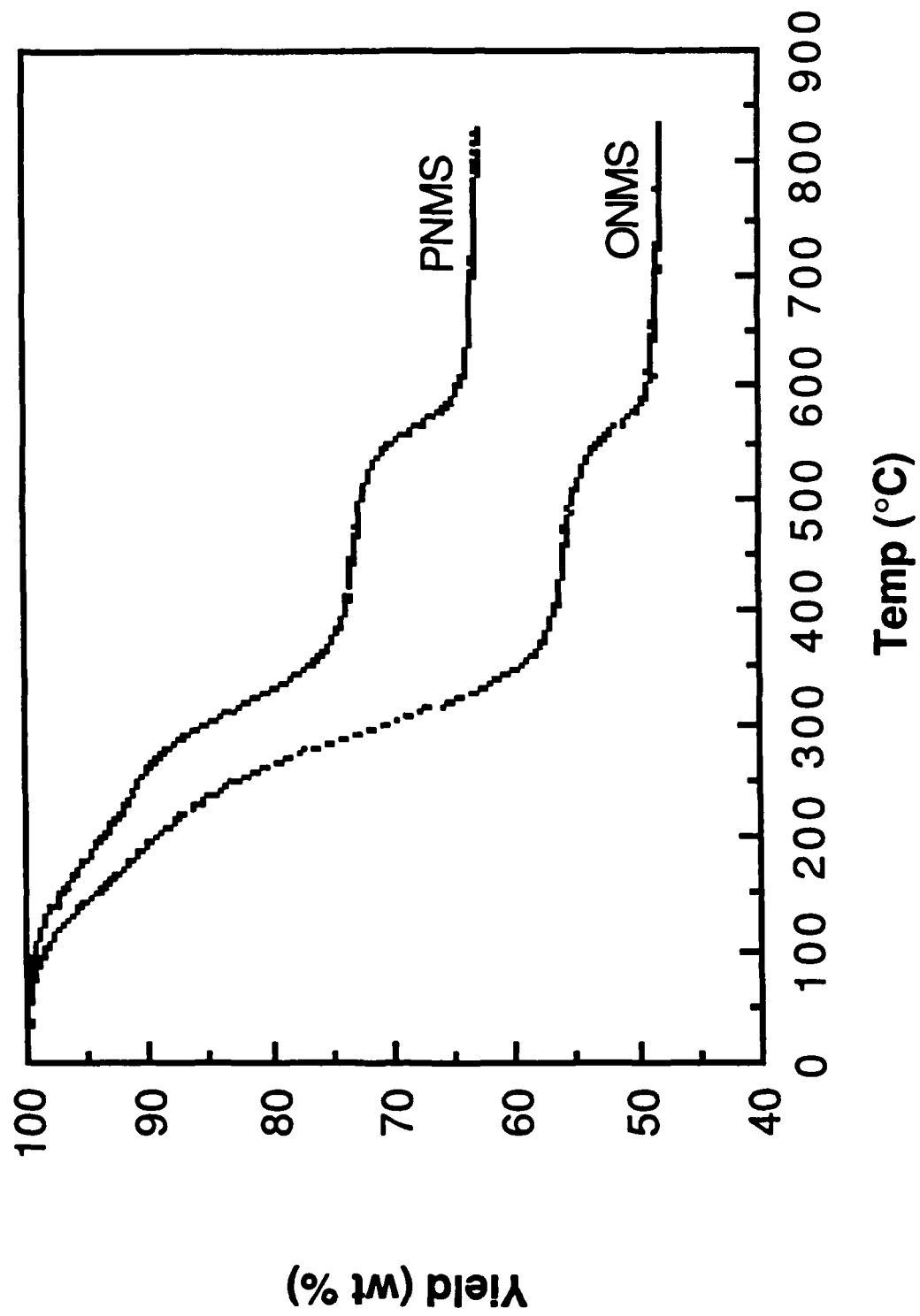   during pyrolysis

PDMS

Yield (wt %)

Temp (°C)

55K

28K

500K   2.6K

Hours of
Reaction

PNMS   65

ONMS   2.1K   0

10^6 10^5 10^4 10^3 10^2

MOLECULAR WEIGHT (daltons)

JA-m-8997-13A

Blum
Figure 3

Temp (°C)

Yield (wt %)

PNMS

ONMS

	R Group	Reaction time(h)[a]	Pyrolysis temp.(°C)[b]	Mn[e] (daltons)	Pyrolysis Yield (wt%)	Elemental Analysis (wt%)				
						C	H	N	Si	O
1	Phenyl	20 (BP)[d]	---	850	---	60.6	5.8	9.6[e]	22.9	0.5
2	Phenyl	20	800	---	50	50.8	1.1	14.3	27.2	5.4
3	Phenyl	50 (BP)[d]	---	1220	---	55.7	5.8	15.7	20.8	1.2
4	Phenyl	50	800	---	69	41.5	1.1	21.4	29.9	6.3
5	Phenyl	50	1600	---	---	33.6	0.2	23.9	39.3	0.7
6	Hexyl	30 (BP)[d]	---	850	---	56.1	11.5	9.1[e]	21.2	0.5
7	Hexyl	30	800	---	24	21.2	0.5	26.6	49.4	1.2
8	Hexyl	56 (BP)[d]	---	2210	---	53.3	9.8	14.8	20.4	2.2
9	Hexyl	56	800	---	36	16.0	0.9	32.2	49.9	0.9
10	Hexyl	56	1600	---	---	9.0	0.1	34.4	54.9	0.5

[a]The polymerization degree in Reaction (4) is extended with time due to changes of reaction conditions.
[b]The 1600°C pyrolysis is the continuation of the 800°C in a Centorr furnace.
[c]M_n was measured by VPO technique.
[d]BP = polymer analysis before pyrolysis.
[e]The oligomer species are substantially linear, but the N:Si mole ratio is lower than 1.00 due to the presence of free silane and silyl terminal groups.

	R Group	Reaction time(h)	Pyrolysis temp.(°C)	Elemental Analysis (mole ratio)				
				C	H	N	Si	O
1	Phenyl	20 (BP)	----	6.17	7.09	0.84	1.00	0.04
2	Phenyl	20	800	4.36	1.16	1.05	1.00	0.35
3	Phenyl	50 (BP)	----	6.25	7.80	1.51	1.00	0.10
4	Phenyl	50	800	3.24	1.03	1.43	1.00	0.37
5	Phenyl	50	1600	2.00	0.14	1.22	1.00	0.03
6	Hexyl	30 (BP)	----	6.18	15.2	0.86	1.00	0.04
7	Hexyl	30	800	1.00	0.28	1.08	1.00	0.04
8	Hexyl	56 (BP)	----	6.10	13.5	1.45	1.00	0.19
9	Hexyl	56	800	0.75	0.51	1.29	1.00	0.03
10	Hexyl	56	1600	0.38	0.05	1.25	1.00	0.01

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Table 2

Polymer Run No.	Temp. (°C)	Ceramic yield (wt%)	Elemental Analysis (wt%)				
			C	H	N	Si	O
ONMS[a]							
1	---	--	23.1	8.8	26.0	41.9	0.5
2	800	50	20.3	1.1	34.5	43.2	0.6
3	1600	41	13.1	0.1	34.1	53.2	0.5
4[c]	800	48	18.6	0.9	34.4	43.5	2.9
PNMS[d]							
5[b]	---	--	21.6	8.0	25.3	44.9	0.5
6	800	61	18.6	1.4	34.5	45.7	0.3
7	1600	49	7.2	0.1	36.4	56.4	0.2

[a] N-methylsilazane before catalytic treatment; M_n = 1200 daltons; viscosity = 5 poise.
[b] Polymer before pyrolysis.
[c] $Ru_3(CO)_{12}$ was mixed with a noncatalyzed oligomer in weight ratio of 1:500 and the mixture was warmed gently only until the solution became homogeneous.
[d] N-methylsilazane after catalytic treatment; M_n = 2500 daltons; viscosity = 140 poise.

B. lum
Table 3

Polymer Run No.	Temp (°C)	Elemental Analysis (mole ratio)				
		C	H	N	Si	O
ONMS						
1	----	1.29	5.88	1.24	1.00	0.02
2	800	1.10	0.71	1.60	1.00	0.02
3	1600	0.57	0.05	1.28	1.00	0.02
4	800	1.00	0.58	1.58	1.00	0.12
PNMS						
5	----	1.12	5.00	1.13	1.00	0.02
6	800	0.95	0.86	1.51	1.00	0.01
7	1600	0.30	0.05	1.29	1.00	0.01

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Table 4

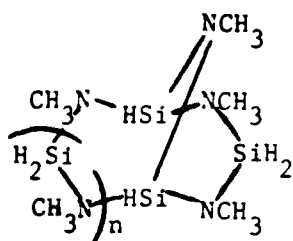| Temp. Range	Pyrolytic Products
70 – 250	Silazanes with MW of 150, 167, 236, 265, 295, 322 amu
250 – 450	Silazanes with MW of 177, 238, 265, 297, 322, 351, 354, 381, 408 amu CH_3NH_2, SiH_4
450 – 600	CH_4(major), C_2H_4, C_2H_6, C_3H_6, C_3H_6, C_3H_8, CH_3CN, $CH_3CH=NH(?)$

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Table 5
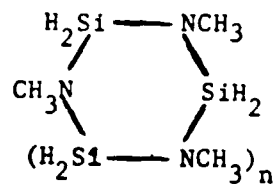
I

n = 1-4

II

n = 4

III

n = 2,3

IV

n = 3

V

n = 1

$H-[H_2SiNCH_3]_n-SiH_3$

VI

n = 2

$H-[H_2SiNCH_3]_n-H$

VII

n = 4,5

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Scheme I

END

12 - 87

DTIC